Chapter 10
Special Concretes

10-1. General

For purposes of this manual, special concretes are considered to be those which contain materials that are not routinely used in conventional structural or mass concrete, those which are not proportioned using procedures given in CRD-C 99, or those which are placed with equipment or by methods which require additional attention be given by the Contracting Officer to assure the required quality is achieved. Those special concretes for which detailed guidance is given in other Corps publications are not discussed in this chapter.

10-2. Preplaced-Aggregate Concrete

a. General. Preplaced-aggregate (PA) concrete is produced by placing coarse aggregate in a form and later injecting a portland-cement-sand fly ash grout, usually with chemical admixtures, to fill the voids. The smaller-size coarse aggregate is not used in the mixture to facilitate grout injection. It is primarily applicable to the repair of existing concrete structures. PA concrete may be particularly suitable for underwater construction, placement in areas with closely spaced reinforcing steel and cavities where overhead contact is necessary, and in areas where low volume change is required. It differs from conventional concrete in that it contains a higher percentage of coarse aggregate since the coarse aggregate is placed directly into the forms with point-to-point contact rather than being contained in a flowable plastic mixture. Therefore, hardened PA concrete properties are more dependent on the coarse aggregate properties. Drying shrinkage of PA concrete may be less than one-half that of conventional concrete, which partially accounts for the excellent bond between PA concrete and existing roughened concrete. The compressive strength of PA concrete is dependent on the quality, proportioning, and handling of materials but is generally comparable to that achieved with conventional concrete. The frost resistance of PA concrete is also comparable to conventional air-entrained concrete assuming the grout mixture has an air content, as determined by ASTM C 231 (CRD-C 41) of approximately 9 percent. PA concrete may be particularly applicable to underwater repair of old structures and underwater new construction where dewatering may be difficult, expensive, or impractical. Bridge piers and abutments are typical of applications for underwater PA concrete construction or repair. A detailed discussion of PA concrete is provided in ACI 304.R.

b. Applications. PA concrete has been used on different types of civil works construction including:

(1) Resurfacing of lock chamber walls.

(2) Underwater repair to lock guide walls.

(3) Resurfacing of spillways.

(4) Construction of plugs to close temporary sluices through a dam.

(5) Filling of temporary fish ladders through a dam.

(6) Scroll case embedment.

c. Materials and proportioning. Intrusion grout mixtures should be proportioned in accordance with ASTM C 938 (CRD-C 615) to obtain the specified consistency, air content, and compressive strength. The grout mixture should also be proportioned such that the maximum w/c complies with those given in Table 4-1. Compressive strength specimens should be made in accordance with ASTM C 943 (CRD-C 84). Compressive strength testing of the grout alone should not be done to estimate the PA concrete strength because it does not reveal the weakening effect of bleeding. However, such testing may provide useful information on the potential suitability of grout mixtures. The ratio of cementitious material to fine aggregate will usually range from about 1 for structural PA concrete to 0.67 for mass PA concrete. A grout fluidifier meeting the requirements of ASTM C 937 (CRD-C 619) is commonly used in the intrusion grout mixtures to offset bleeding, to reduce the w/c and still provide a given consistency, and to retard stiffening so that handling times can be extended. Grout fluidifiers typically contain a water-reducing admixture, a suspending agent, aluminum powder, and a chemical buffer to assure timed reaction of the aluminum powder with the alkalies in the portland cement. Products proposed for use as fluidifiers which have no record of successful prior use in PA concrete may be accepted contingent on successful field use. ASTM C 937 requires that intrusion grout made as prescribed for acceptance testing of fluidifiers have an expansion within certain specified limits which may be dependent on the alkali content of the cement used in the test. Experience has shown, however, that because of the difference in mixing time and other factors, expansion of the field-mixed grout ordinarily will range from 3 to 5 percent. If, under field conditions, expansion of less than 2 percent or more than 6 percent occurs, adjustments to the fluidifier should be made to bring the expansion within these limits. The fluidifier should be tested under field conditions with job materials and equipment as soon as practicable so that sufficient time is available to make adjustments in the fluidifier if necessary. If the aggregates are potentially alkali reactive, the total alkali content of the portland cement plus fluidifier added to increase expansion should not exceed 0.60 percent, calculated as equivalent sodium oxide by mass of cement. The grout submitted for use may exhibit excess bleeding if its cementitious material to fine aggregate ratio is different than that of the grout mixture used to evaluate the fluidifier. Expansion of the grout mixture should exceed bleeding at the expected in-place temperatures. Grout should be placed in an environment where the temperature will rise above 40 °F, since expansion caused by the fluidifier ceases at temperatures below 40 °F. This condition is normally readily obtainable when PA concrete is placed in massive sections or placements are enclosed by timber forms. If an air-entraining admixture is used in the PA concrete, adjustments in the grout mixture proportions may be necessary to compensate for a significant strength reduction caused by the combined effects of entrained air and the hydrogen generated by the aluminum powder in the fluidifier. However, these adjustments must not reduce the air content of the mixture to a level that compromises its frost resistance. The largest practical NMSA should be used to increase the economy of the PA concrete. A 37.5-mm (1-1/2-in.) NMSA will typically be used in much of the PA concrete; however, provisions are made for the use of 75-mm (3-in.) NMSA when it is considered appropriate. It is not expected that many situations will arise where the use of aggregate larger than 50 mm (2 in.) will be practical. Pozzolan is usually specified to increase flowability of the grout.

d. Preplacing aggregate. Care is necessary in preplacing the coarse aggregate if excessive breakage and objectionable segregation are to be avoided. The difficulties are magnified as the nominal maximum size of the aggregate increases, particularly when two or more sizes are blended. Therefore, the Contractor's proposed methods of placing aggregate should be carefully reviewed to ensure that satisfactory results will be obtained. Coarse aggregate must be washed, screened, and saturated immediately prior to placement to remove dust and dirt, and to eliminate coatings and undersize particles. Washing in forms should never be permitted because fines may accumulate at the bottom.

e. Contaminated water. Contaminated water is a matter of concern when PA concrete is placed underwater. Contaminants present in the water may coat the aggregate and adversely affect the setting of the cement or the bonding of the mortar to the coarse aggregate. If contaminants in the water are suspected, the water should be tested before construction is permitted. If contaminants are present in such quantity or of such character that the harmful effects cannot be eliminated or controlled, or if the construction schedule imposes a long delay between aggregate placement and grout injection, PA concrete should not be used.

f. Preparation of underwater foundations. Difficulty has been experienced in the past with cleanup of foundations in underwater construction when the foundation material was glacial till or similar material. The difficulty develops when as a result of prior operations, an appreciable quantity of loose, fine material is left on the foundation or in heavy suspension just above the foundation. The fine material is displaced upward into the aggregate as it is being placed. The dispersed fine material coats the aggregate or settles and becomes concentrated in the void spaces in the aggregate just above the foundation thus precluding proper intrusion and bond. Care must, therefore, be exercised to ensure that all loose, fine material is removed insofar as possible before placement of aggregate is allowed to commence.

g. Pumping. Pumping of grout should be continuous insofar as practical; however, minor stoppages are permissible and ordinarily will not present any difficulties when proper precautions are taken to avoid plugging of grout lines. The rate of pumping should be regulated by use of sounding wells so that the preplaced aggregate is slowly intruded to allow complete and uniform filling of all voids. The rate of grout rise within the aggregate should be controlled to eliminate cascading of grout and to avoid form pressures greater than those for which the forms were designed. For a particular application, the grout injection rate will depend on form configuration, aggregate grading, and grout fluidity.

h. Joint construction. A cold joint is formed in PA concrete when pumping is stopped for longer than the time it takes for the grout to harden. When delays in grouting occur, the insert pipes should be pulled just above the grout surface before the grout stiffens, and then rodded clear. When pumping is ready to resume, the pipes should be worked back to near contact with the hardened grout surface and then pumping resumed slowly for a few minutes. Construction joints are formed in a similar manner by stopping grout rise approximately 12 in. below the aggregate surface. Care must be taken to prevent dirt and debris from collecting on the aggregate surface or filtering down to the grout surface. If construction joints are made by bringing the grout to the surface of the coarse aggregate, the joint surfaces should be cleaned and prepared as discussed in paragraph 7-6 d of this manual.

i. Grouting procedure. The two patterns for grout injection are the horizontal layer and the advancing slope. Regardless of the system used, grouting should start from the lowest point in the form.

(1) Horizontal layer. In this method grout is injected through an insert pipe to raise the grout until it flows from the next insert hole 3 to 4 ft above the point of injection. Grout is then injected into the next horizontally adjacent hole, 4 or 5 ft away, and the procedure is repeated sequentially around the member until a layer of coarse aggregate is grouted. Successive layers of aggregate are grouted until all aggregate in the form has been grouted.

(2) Advancing slope. The horizontal layer method is not practical for construction of such slabs when the horizontal dimensions are large. In situations such as this, it becomes necessary to use an advancing slope method of injecting grout. In this method, intrusion is started at one end of the form and pumping continued until the grout emerges on the top of the aggregate for the full width of the form and assumes a slope which is advanced and maintained by pumping through successive rows of intrusion pipes until the entire mass is grouted. In advancing the slope, the pumping pattern is started first in the row of holes nearest the toe of the slope and continued row by row up the slope (opposite to the direction of advance of slope) to the last row of pipes where grouting has not been completed. This process is repeated, moving ahead one row of pipes at a time as intrusion is completed.

(3) Grout insert pipes and sounding devices. The number required and the location and arrangement of grout insert pipes will depend on the size and shape of the work being constructed. For most work, grout insert pipes will consist of pipes arranged vertically and at various inclinations to suit the configurations of the work. The guide specification provides for the option of the diameter of the grout insert pipes being either 3/4, 1, or 1-1/2 in. Generally, either a diameter of 3/4 or 1 in. would be allowed for structural concrete having a maximum size aggregate of 37.5 mm (1-1/2 in.) or less. If the preplaced aggregate has a maximum size larger than 37.5 mm (1-1/2 in.), the grout insert pipes should be 1-1/2 in. in diameter. Intrusion points should be spaced about 6 ft apart; however, spacing wider than 6 ft may be permissible under some circumstances, and spacings closer than 6 ft will be necessary in some situations. Normally, one sounding device should be provided for each four intrusion points; however, fewer sounding devices may be permissible under some circumstances. In any event, there should be enough sounding devices, and they should be arranged so that the level of the grout at all locations can be accurately determined at all times during construction. Accurate knowledge of the grout level is essential to:

(a) Check the rate of intrusion.

(b) Avoid getting the grout too close to the level of the top of the aggregate when placement of the aggregate and intrusion are progressing simultaneously.

(c) Avoid damage to the work which would occur if a plugged intrusion line were washed out while the end of the line was within the grout zone.

Sounding devices usually consist of wells (slotted pipes) through which the level of the grout may be readily and accurately determined. If sounding devices other than wells are proposed, approval should be based on conclusive demonstration that such devices will readily and accurately indicate the level of the grout at all times. In repairing vertical surfaces, such as lock chamber walls or sloping surfaces which are substantial distances and are relatively thin (up to about 2 ft thick), the grout is brought up uniformly from the bottom. Intrusion points for such work should be arranged in horizontal rows with the rows spaced not more than 4 ft apart horizontally. Holes in adjacent horizontal rows should be staggered so that a hole in any row is at the midpoint of the space between holes in the adjacent rows above and below. Intrusion is controlled by pumping through all holes in each horizontal row until grout flows from all holes in the row above. Grouting then proceeds through the next row above after the holes below, which have just been grouted are plugged. The process is repeated until a section is completed. The bottom row of holes should be placed at the bottom of the form.

j. Finishing unformed surfaces. If a screeded or troweled finish is required, the grout should be brought up to flood the aggregate surface and any diluted grout should be removed. A thin layer of pea gravel or 3/8- to 1/2-inch crushed stone should then be worked into the surface by raking and tamping. After the surface has stiffened sufficiently, it may be finished as required. A finished surface may also be obtained on PA concrete by adding a bonded layer of conventional concrete of the prescribed thickness to the PA concrete surface. The PA concrete surface should be cleaned and grouted prior to receiving the topping.

10-3. Underwater Concrete

a. General. For underwater concrete placements to be successful, careful planning and execution are essential. The location and size of the area to be concreted should be well defined and thoroughly cleaned so that it is free of mud, silt, and debris. The extent of the cleaning effort will be determined largely by whether the concrete is being placed into a new structure or being used to repair an existing structure. All marine growth, sediment, debris, and deteriorated concrete must be removed prior to placing new concrete. Waterjets and self-propelled vehicles have been effective in most cleaning applications. Airlifts should be used to remove sediment and debris from depths of 25 to 75 ft. If the concrete is being used to repair an existing structure, an appropriate number of anchors should be grouted into the existing concrete to tie the new concrete to the existing concrete. The concrete must be protected from the water until it is in place so that the cement fines cannot wash away from the aggregate. This protection can be achieved through the proper use of placing equipment, such as tremies and pumps. The velocity of the water immediately adjacent to the placement should not exceed 5 ft/sec. The quality of the in-place concrete can be enhanced by the addition of an AWA which increases the cohesiveness of the concrete. Concrete mixtures to be placed underwater must be highly workable and cohesive. The degree of workability and cohesiveness can vary somewhat depending upon the type of placing equipment used and the physical dimensions of the area to be filled with concrete. A dense, homogeneous mass of concrete having hardened properties equivalent to those of concrete placed in the dry should be the result of a good underwater concrete operation.

b. Tremie concrete. A massive and confined placement, such as a cofferdam or a bridge pier, could be completed with a conventional tremie concrete mixture. The desired workability can normally be produced by using 19.0- or 37.5-mm (3/4- or 1-1/2-in.) NMSA and a w/c not exceeding 0.45. An increase in fine aggregate content of approximately 6 percent, as compared to a conventional concrete mixture, may be necessary. Rounded aggregates are preferred over crushed aggregates for both coarse and fine sizes. Listed below is a typical mixture for a conventional tremie mixture:

Portland cement 600 lb/cu yd
Fly ash 100 lb/cu yd
19.0-mm (3/4-in.) NMS natural gravel
Natural sand
Sand-aggregate ratio = 0.45
w/c = 0.45
WRA
Air content = 6 %
Slump = 6 to 8 in.

Mixtures of this type must be fully protected from exposure to water until in place. Whether being placed by tremie or pump, it is mandatory that the seal be maintained. Once concreting is underway, the bottom of the pipe should be kept buried in the concrete about 5 ft below the surface of the concrete. AWA’s can be used in these mixtures but are not necessary, although their use should enhance the fresh properties of the concrete. Spacing of tremie pipes should not exceed 15 ft. A more complete discussion of tremie concreting practices is given in ACI 304R.

c. Pumped concrete for use underwater. Many repair situations require that the concrete flow laterally in thin lifts for a substantial distance. This exposes the concrete to much water while being placed. For this type of placement, an AWA should be used to enhance the cohesiveness of the concrete. The cohesiveness and flowability required cannot normally be obtained without use of an AWA. Water-reducing or HRWRA’s are usually necessary as well. Trial batches must be made to ensure compatibility between AWA’s, WRA’s, and HRWR’As. The desired workability can normally be produced with rounded aggregates of 19.0-mm (3/4-in.) NMS or smaller and a w/c not exceeding 0.45. An increase of approximately 6 percent in fine aggregate content, as compared to a conventional concrete mixture, may be necessary. When a repaired area will be subjected to abrasion-erosion, silica fume should be considered to enhance the hardened properties of the concrete. Silica fume will also increase the cohesiveness of the fresh concrete mixture. Listed below is a typical mixture for proportioning an underwater concrete mixture for use in repairing an existing structure:

Portland cement 600 lb/cu yd
Fly ash 30 lb/cu yd
Silica fume 40 lb/cu yd
19.0-mm (3/4-in.) NMS or smaller natural gravel
Natural sand
Sand-aggregate ratio = 0.45
w/c = 0.40
AWA
WRA or HRWRA
Air content = 6 %
Slump = 8 to 10 in.

Pumping is the preferred method of placement, although tremies may be used on some repair jobs. Pumping distances should be kept to a minimum. If the pumping distance exceeds 250 ft, pumping pressures will likely increase significantly due to the increased cohesiveness imparted by the AWA. Excessive pumping pressures will necessitate relocating the pump, using staged pumps to shorten the pumping distance, or modifying the concrete mixture or reducing the amount of AWA's. Some adjustments may reduce the cohesiveness of the concrete, making it more susceptible to washout. If the pumping distance is 150 ft or less, the cohesiveness imparted by an AWA actually improves the pumpability of concrete. When AWA's are used, it is not as critical to keep the discharge end of the tremie or the pump line embedded in the concrete as it is when they are not used. However, the concrete should not be unnecessarily exposed to water during placement. Once in place, concretes of this type can flow up to 30 ft without harmful washout or segregation. Pumped concrete is discussed in detail in paragraph 10-6 of this manual. Additional information on pumped concrete for use under water is given in WES Technical Report REMR-CS-18 (Neeley 1988) and EM 1110-2-2002, "Evaluation and Repair of Concrete Structures."

10-4. Blockout Concrete

a. General. The use of blockouts in concrete members is often necessary to embed seats, guides, rails, piping, and electrical and mechanical systems into concrete placements. Prior to placement of blockout concrete, the blockout or recess should be carefully inspected to assure all surfaces are thoroughly cleaned of all loose material, oil, grease, and other material which might reduce or destroy bond between surfaces of the blockout or recess and the new concrete. Care should also be exercised in assuring that blockout concrete is properly consolidated, particularly in those blockouts or recesses which are heavily congested with a combination of embedments and reinforcing steel.

b. Blockout concrete proportions. Blockout concrete is normally proportioned to meet the same strength criteria as adjacent concrete. The NMSA is usually 19.0 mm (3/4 in.). Bonding of the blockout concrete to the adjacent formed concrete surfaces is most important. These surfaces must be cleaned of any laitance and any oil, grease, or foreign matter. Cleanup of these surfaces should be the same as for any other surface to which concrete is to be bonded, although sandblasting or high-pressure water jet blasting is not usually necessary for block outs on vertical surfaces. The fluidifying-expanding agent should be used in such proportion that the paste portion of the blockout concrete, when tested separately, will have an expansion of 2 to 4 percent when tested in accordance with ASTM C 940. An expansive admixture conforming to ASTM C 937 (CRD-C 619) should be specified for all vertical blockouts and any other blockouts which are formed or otherwise confined on all sides. Where the blockout is on a horizontal surface and the top of the blockout concrete is to be hand finished, the expansive admixture should not be used. An epoxy bonding compound meeting ASTM C 881, Type V (CRD-C 595), has been successfully used for bonding of blockout concrete to adjacent concrete although timing can be critical. The new concrete must be placed while the epoxy is still tacky and before it hardens.

10-5. High-Strength Concrete

a. General. High-strength concrete has seen increasing use in recent years as compressive strength requirements have increased and new applications have been developed. Early applications emphasized its use to reduce column dimensions. It has now been used to meet special project objectives such as in large composite columns, stiffer structures, bridges, stilling basins, and structures subject to chemical attack. The increased use of high-strength concrete has, in turn, prompted the application of more stringent quality control requirements. A thorough discussion of high-strength concrete is given in ACI 363R.

b. Definition. The definition of high-strength concrete is concrete having a 28-day design compressive strength over 6,000 psi (41 MPa) (ACI 116R). In regions where concretes having strengths up to 5,000 psi are readily available, 9,000 psi might be considered to be high-strength concrete. However, in regions where concrete having a compressive strength of 9,000 psi is readily available, 12,000 psi might be considered to be high-strength concrete. In many instances, the required compressive strength is specified at 56- or 90-days age rather than 28-days age to take better advantage of pozzolans in the concrete.

c. Materials. When high-strength concrete is to be used, all materials must be carefully selected. Items to be considered in selecting materials include cement characteristics, aggregate size, strength, shape, and texture, and the effects of chemical admixtures and pozzolans. High-strength concretes are typically proportioned with high cement contents, low w/c, normal weight aggregate, chemical admixtures, and pozzolans. Trial mixtures are essential to ensure that required concrete properties will be obtained.

d. Cement type. The choice of portland cement is very important. Type I cement is appropriate for use in most high-strength concrete. If high initial strength is required, such as in prestressed concrete, Type III cement may be more appropriate. However, the high cement contents associated with high-strength concretes will cause a high temperature rise within the concrete. If the heat evolution is expected to be a problem, a Type II moderate-heat-of-hydration cement can be used, provided it meets the strength-producing requirements. However, even within a given type of cement, such as Type I, II, or III, different brands can have different strength development characteristics because of the variations in their physical and chemical compositions.

e. Cement content. Cement contents typically range from 660 to 940 lb/yd^3. However, higher strengths do not always accompany higher cement contents. The concrete strength for any given cement content will vary with the water demand of the mixture and the strength-producing characteristics of the cement being used. The optimum cement content will depend upon the combinations of all materials being used and is best determined by trial batches.

f. Aggregates. The choice of aggregates is very important to the ultimate strength that a high-strength concrete will develop since they occupy the largest volume of any of the constituents in the concrete. Most high-strength concrete has been produced using normal weight aggregates. Some high-strength lightweight aggregates and heavyweight aggregates have also been used successfully in high-strength concretes. In general, crushed coarse aggregates, 19.0-mm (3/4-in.) nominal maximum size or smaller, are preferred for high-strength concretes because their shape and surface texture enable the cement paste to bond to them better than rounded natural aggregates. Smaller size aggregates have better bond strengths and less severe stress concentrations around the particles. The ideal aggregate should be clean, cubical, angular, 100-percent crushed aggregate with a minimum of flat and elongated particles. The volume of coarse aggregate can usually be increased up to 4 percent from that recommended in ACI 211.1 for conventional concretes. Natural fine aggregates are preferred because they require less mixing water and provide better workability. Since the concrete has a high cement content, sands having a high fineness modulus (about 3.0) usually give better workability and strength. Sands having fineness moduli of 2.5 and below usually increase the water demand and give the concrete a sticky consistency, making it more difficult to place.

g. Pozzolans. Pozzolans in quantities ranging from 15 to 40 percent by mass of cement are frequently used to supplement the portland cement in high-strength concrete. Silica fume is generally used in amounts ranging from 5 to 10 percent by mass of cement. The volume increase in cementitious materials resulting from the addition of a pozzolan is usually offset largely by a decrease in the fine aggregate content. Depending on the type of pozzolan used, the water demand of the concrete mixture may be increased or decreased. When silica fume is used, the water demand will be increased and make the use of an HRWRA necessary. See paragraph 10-10 of this manual for more information on silica-fume concrete.

h. Use of HRWRA. HRWRA's are frequently used in high-strength concrete to lower the w/c. They can also be used to increase the workability of the concrete. In some cases, an HRWRA may be used in combination with a conventional WRA or a retarding admixture to reduce slump loss. Depending on the specified w/c, the required workability, and the materials being used, a conventional WRA used at a high dosage may provide the necessary water reduction. Larger-than-normal dosages of air-entraining admixtures are usually required to entrain air in high-strength concretes due to the high cement contents.

i. Workability. Due to their cohesiveness, high-strength concretes can be more difficult to place than conventional concretes. The mixture should be easy to vibrate and mobile enough to pass through closely spaced reinforcement. A slump of about 4 in. will usually provide the required workability. However, all structural details should be considered prior to specifying the fresh properties of the concrete mixtures. Also, the rapid slump loss exhibited by many high-strength concretes should be considered. Slumps of less than 3 in. have been difficult to place without special equipment and procedures.

j. Proportioning. More laboratory trial batches may be necessary to properly proportion a high-strength concrete mixture than would be required to proportion a conventional concrete mixture. Once a mixture has been proportioned in the laboratory, field testing with production-size batches is recommended. Frequently, the strength level that can be reasonably achieved in the field will be lower than that attained in the laboratory batches. The water demand may also vary from that determined in the laboratory. Production and quality control procedures can be evaluated more effectively when production-size batches are produced using the equipment and personnel that will be doing the actual work.

k. Material handling. The control, handling, and storage of materials need not be significantly different from the procedures used for conventional concrete. However, some emphasis on critical points is prudent. The temperature of all ingredients should be kept as low as possible prior to batching. It may be necessary to make provisions to lower the initial temperature of the concrete by using chilled water, ice, or liquid nitrogen. Delivery time should be reduced to a minimum and special attention given to scheduling and placing to avoid having trucks waiting to unload. Where possible, the batching facilities should be located at or near the job site to reduce haul time. Extended haul times can result in a significant increase in temperature and loss of slump and should be avoided.

l. Preparation for placing. Preparation for placing high-strength concrete should include recognition that certain unusual conditions will exist before any placement begins. Since the effective working time of the concrete is expected to be reduced, preparation must be made to transport, place, consolidate, and finish the concrete as quickly as possible. Proper planning, skilled workmen, adequate equipment, and stand-by equipment are all essential to a successful high-strength concrete placement.

m. Curing. Proper curing is critical to the production of high-strength concrete. The potential strength and durability of any concrete, especially high-strength concrete, will be fully developed only if it is properly cured for an adequate period prior to being placed in service. Water curing of high-strength concrete, especially at early ages, is required because of the low w/c's. If the w/c is below 0.40, the degree of hydration will be significantly reduced if free water is not provided during curing. Water curing will allow maximum hydration of the cement.

n. Testing. Since much of the interest in high-strength concrete is limited primarily to compressive strength, these measurements are of primary concern in the testing of high-strength concretes. Careful attention should be given to all details of the test methods being used while fabricating, curing, and testing compressive strength specimens. Standard specimens are 6-in.-diameter by 12-in.-high cylinders; however, 4-in.-diameter by 8-in.-high cylindrical specimens have also been used to determine the compressive strength of high-strength concretes. The 4-in.-diameter by 8-in.-high specimens usually exhibit somewhat higher compressive strengths and more variability than the standard size specimens. Even so, proper testing procedures and a suitably accurate and stiff testing machine are more critical to attaining good results than is the specimen size. High-strength sulfur mortar may be used to cap specimens having compressive strengths up to 10,000 psi. Specimens expected to have compressive strengths above 10,000 psi should have their ends formed or ground to the required tolerance. A caution should be added that these higher-strength concretes require a corresponding larger capacity compression testing machine.

10-6. Pumped Concrete

a. General. Pumped concrete can be used for most structural concrete construction but is most useful where space for construction equipment is limited or access is difficult. Concrete pumps can be either truck- or trailer-mounted and range from small units, exerting pressures from 250 to 300 psi and outputs of 15 to 30 yd^3/hr, to large units, exerting pressures of 1,000 psi and outputs up to 150 yd^3. The effective capacity of a pump depends not only on the pump itself but also on the complete system. Several factors including line length, number of bends in the line, type of line, size of line, height to which the concrete is being pumped, and the concrete mixture affect the effective working capacity of a concrete pump. An excellent reference is ACI 304.2R.

b. Pump lines. Pump lines are usually a combination of rigid pipe and heavy-duty flexible hose. Acceptable rigid pipe can be made of steel or plastic and is available in sizes from 3 to 8 in. in diameter. Aluminum alloy pipe should not be used as pump line. Flexible hose is made of rubber, spiral wound flexible metal, and plastics. It is useful in curves, difficult placement areas, and as connections to moving cranes but exhibits greater line resistance to the movement of concrete than rigid pipe and may have a tendency to kink. To obtain the least line resistance, the pipeline should be made up primarily of rigid pipe with flexible hose only where necessary. If possible, the pipeline should be of one size and laid out so as to contain a minimum number of bends.

c. Mixture proportions. Concrete mixture proportions of pumpable mixtures are essentially the same as those to be placed by other methods, except that more emphasis should be placed on the grading of the fine aggregates. Concretes which are pumped must be cohesive. Harsh mixtures do not pump well. Pressure exerted by the pump can force the mortar away from the coarse aggregate causing a blockage in the line if the mixture is not proportioned properly. The cement content will generally be somewhat higher for pumped mixtures than those of mixtures placed by conventional methods. The higher fine aggregate content will have a higher water demand, which in turn will require a higher cement content. However, extra cement should not be used to correct pumping deficiencies resulting from poorly graded aggregates. It is usually more preferable to correct deficiencies in the fine aggregates by blending in additional fine aggregates or pozzolan than by adding cement.

d. Coarse aggregates. The nominal maximum size of the coarse aggregate is limited to one-third of the smallest inside diameter of the pump line for crushed aggregates or 40 percent of the smallest inside diameter of the pump line for well-rounded aggregates. Oversize particles should be eliminated. A higher mortar content will be necessary to effectively pump a concrete containing crushed aggregates than for a concrete containing rounded aggregates.

Depending upon the type and size of the coarse aggregate, it may be necessary to reduce the coarse aggregate content from 5 to 10 percent as compared to mixtures placed by conventional methods.

e. Fine aggregate. The properties of fine aggregates are more critical in proportioning pumpable mixtures than are the properties of the coarse aggregates. Together with the cement and water, the fine aggregates constitute the mortar which conveys the coarse aggregates in suspension through the pump line. Fine aggregates should conform to the requirements given in ASTM C 33 (CRD-C 133) for fine aggregates. In addition, for pump systems having lines 6-in. in diameter and smaller, 15 to 30 percent of fine aggregate should pass the 300-µm (No. 50) sieve and 5 to 10 percent should pass the 150-µm (No. 100) sieve. Fine aggregates that are deficient in either of these two sizes should be blended with selected finer aggregates to produce the desired grading. Pumpability of concrete is generally improved with a decrease in the fineness modulus. Fine aggregates having a fineness modulus between 2.40 and 3.00 are generally satisfactory provided that the percentages passing the 300- and 150-µm (No. 50 and No. 100) sieves meet the previously stated guidelines. Fineness modulus values alone without stipulations on the finer sizes may not produce satisfactory results. Both manufactured fine aggregates and natural sands can be used in pumped mixtures provided their gradings are appropriate; however, natural sands are preferred due to their rounded shape.

f. Slump. The water requirements to establish the optimum slump and to maintain control of that slump throughout the course of a pumping placement are both extremely important factors. Concretes having slumps less than 2 in. when delivered to the pump are difficult to pump. Concretes having slumps over 6 in. can segregate causing a blockage in the pump line and may require a pump aid to increase the cohesiveness of the concrete to prevent the aggregate from separating from the mortar during pumping. It is much more important to obtain a cohesive concrete through proper proportioning than to try to overcome deficiencies by adding extra water. In fact, the use of excess water creates more problems than it solves.

g. Admixtures. Materials which improve workability, such as water-reducing, high-range water-reducing, and air-entraining admixtures, as well as pozzolans, usually improve pumpability. It is common to experience a decrease in air content during pumping. The specified air contents required for durability should be obtained at the point of placement in the structure. Therefore, it may be necessary to entrain a higher air content into the concrete mixture prior to pumping. Pumping aids are admixtures which can reduce friction, reduce bleeding, and increase cohesiveness, all of which make concretes pump easier.

h. Pumpability tests. There is no standard laboratory test method available to accurately test the pumpability of a concrete mixture. Testing a concrete mixture for pumpability involves duplicating anticipated job conditions from beginning to end. A full-scale field test for pumpability should be considered to evaluate both the mixture proportions and pumping equipment. Prior use of a mixture and pumping equipment on another job may furnish evidence of pumpability if job conditions are duplicated.

i. Planning. Proper planning of the entire pumping operation including pump location, line layout, placing sequence, and concrete supply will result in savings of time and expense. The pump should be as near the placement area as possible. Concrete delivery systems should have easy access to the pump. Lines from the pump to the placement area should be made up primarily of rigid pipe and contain a minimum number of bends. For large placement areas, alternate lines should be laid for rapid connection when required, and standby power and pumping equipment should be readily available to replace an initial piece of equipment should a breakdown occur.

j. Other requirements. When pumping downward 50 ft or more, an air release valve at the middle of the top bend will prevent vacuum or air buildup. When pumping upward, a shutoff valve near the pump will prevent the reverse flow of concrete during the fitting of cleanup equipment or when working on the pump. Direct communication should be maintained between the placing crew and the pump operator. Good communication between the pump operator and the concrete batch plant is also important. It is desirable to have the concrete delivery such that the pumping can proceed continuously. When a delay occurs, it may be difficult to start the concrete moving in the line again, especially if the delay has been for a considerable length of time. This critical delay time will depend upon such factors as the concrete mixture, temperature, length of pipeline, and type of pump. It may be necessary to clean the line and start again if the delay becomes extended. A grout or mortar should be used to lubricate the pipeline anytime pumping is started with clean lines, but it should not be pumped into the forms.

k. Quality verification. A high level of quality control must be maintained to provide assurance that the concrete is of the desired quality. Concrete should be sampled at both ends of the pumpline to determine what, if any, changes in the slump, air content, and other concrete properties occur during pumping. However, the quality of the concrete being placed in the structure can only be measured at the placement end of the pumpline.

10-7. Fiber-Reinforced Concrete

a. General. Fiber-reinforced concrete (FRC) is concrete which contains dispersed, randomly oriented fibers. Fiber-reinforced concrete and fiber-reinforced shotcrete have been used for pavements, overlays, patching, floor slabs, refractory materials, hydraulic structures, thin shells, armor for jetties, rock slope stabilization, tunnel linings, and precast units since the mid 1960's. Fibers have been produced from steel, plastic, glass, and natural materials in various shapes and sizes. ASTM A 820 (CRD-C 539) is the specification which covers minimum standards for steel fibers intended for use in fiber-reinforced concrete. The size of fibers are usually described by their aspect ratio, which is the fiber length divided by an equivalent fiber diameter. Aspect ratios typically range from about 30 to 150. Some steel fibers are collated with water-soluble glue into bundles of 10 to 30 fibers to facilitate handling and mixing. Uniform dispersion of fibers through the concrete provides isotropic strength properties not common to conventionally reinforced concrete. Additional information on steel FRC may be found in ACI 544.1R, ACI 544.2R, ACI 544.3R, and ACI 544.4R.

b. Advantages and limitations. Steel fibers increase the first crack flexural strength, direct tensile strength, and splitting tensile strength. Compressive strengths may exhibit a minor increase. Fibers can increase the ductility of concrete substantially depending on the type and amount of fiber present in the concrete. However, balling of fibers in the mixer hinders uniform distribution and reduces workability. This can impose an upper limit beyond which benefits gained from the fibers are no longer realized. This upper limit depends upon the type and size of fibers and the mixing procedures being used. Because of mixing and placing considerations, approximately 2 percent by volume of the total concrete mixture is considered the practical upper limit for most types of fibers in field placements. Higher percentages could be used when the fibers are a type that do not interlock significantly. However, fibers with hooked ends can achieve essentially the same properties as straight fibers of the same aspect ratio using less fiber.

c. Toughness. Steel fibers increase the toughness, which is a measure of the energy absorption capacity of concrete. The increase in toughness depends on the type, amount, and aspect ratio of the fibers. In general, crimped fibers, surface-deformed fibers, and fibers with hooked ends produce toughness indexes greater than those for smooth straight fibers at the same volume concentration.

d. Performance characteristics. Steel fiber concrete has shown good resistance to dynamic forces and a significant increase in fatigue strength. Fatigue strength tends to increase with an increase in fiber loading, and the crack width under fatigue loading tends to decrease. The benefits that a conventional concrete mixture gains from steel fibers depend primarily on the loading of fibers and the size, shape, and aspect ratio of the fibers. Steel-fiber concrete has not shown excessive corrosion of the steel fibers when placed in corrosive environments. The corrosion has been confined to the fibers actually exposed to the surface. Fiber-reinforced concrete has shown good resistance to cavitation forces resulting from high-velocity water flow and to the damage caused by the impact of large waterborne debris at high velocity. However, FRC exhibits poor resistance to abrasion that occurs from the grinding action of rocks and debris carried in low-velocity water. Therefore, FRC shall not be used in areas subject to underwater abrasion.

e. Mixture proportioning. Fiber-reinforced concrete generally has higher cement and fine aggregate contents and smaller NMSA than conventional concrete. Coarse aggregates are generally 19.0-mm (3/4-in.) nominal maximum size or smaller. Pozzolans are often used to reduce the relatively high cement contents. Chemical admixtures are commonly used for air-entrainment, water reduction, and workability improvement. To ensure uniform mixing, the maximum aspect ratio of round wire and flat strip fibers should be no greater than 100. Characteristically, an FRC mixture will experience a decrease in workability as the fiber loading increases. Experience suggests w/c between 0.40 and 0.60 and cementitious contents between 500 and 900 lb/yd^3 are required when steel fibers are used to produce adequate paste to coat the large surface area of the fibers. The percentage of fine aggregate to total aggregate will range from 45 to 60 percent depending on the NMSA and aggregate gradings. Once mixture proportions have been developed, a full-size trial batch should be produced in the plant and mixer to be used for the project prior to the actual placement of the fiber-reinforced concrete.

f. Batching and mixing. Mixing of FRC can be accomplished by different methods, depending on the job requirements and the facilities that are available. The ultimate goal is to have a uniform dispersion of the fibers and prevent the segregation or balling of the fibers during mixing. Segregation or balling of the fibers is related to several factors, the most important of which appears to be the aspect ratio. Other factors such as the fiber loading, coarse aggregate size, aggregate grading, w/c ratio, and method of mixing can also influence the fiber distribution. Increases in aspect ratio, fiber loading, coarse aggregate size, and quantity of coarse aggregate intensify balling tendencies. Most fiber balling occurs as the fibers are added to the concrete mixture and can be eliminated by controlling the rate of fiber addition or by the use of collated fibers. If collated fibers are used, they may be dumped directly into the concrete mixture as the last step. Subsequent mixing action separates and disperses the fibers throughout the mixture. If loose fibers are used, they must be added slowly and uniformly to the mixture in such a way as to prevent large clumps of fibers from entering the mixture. The fibers can be added to the aggregates prior to introduction of the cement and water or as the last step. The method of introducing the fiber into the mixture should be tried in the field during a trial mixture. Fiber balling that occurs after fiber addition can usually be attributed to overmixing or poor mixture proportions, such as too much coarse aggregate or a fiber loading that is too high.

g. Placement. A fiber-reinforced concrete mixture will generally require more effort to move and consolidate into forms. The fibrous nature of the mixture makes the use of shovels or hoes difficult. Forks and rakes are preferred for handling low-slump mixtures. Properly controlled internal vibration is acceptable, but external vibration of the forms and exposed surface is preferable to prevent fiber segregation. Standard finishing and curing methods can be used with FRC with one exception. If a textured surface is desired, a burlap drag is not recommended as the fibers can hang up in the burlap. A textured surface can be obtained by brooming with a stiff brush, but it should be delayed as long as possible to prevent pulling fibers to the surface.

h. Workability. The inverted slump cone test, described in ASTM C 995 (CRD-C 67), should be used as an indicator of workability of FRC. The advantage of the inverted slump cone test over the slump test is that it takes into account the mobility of concrete which comes about because of vibration. Reliance on the slump test often results in the use of excessive amounts of water in an attempt to increase the slump without improving workability.

i. Pumping. Fiber-reinforced concrete with fiber loadings up to 1.5 percent by volume of the total mixture have been pumped using 5- to 6-in.-diam pipelines. Steel FRC can be produced using conventional shotcrete equipment.

j. Other fibers. Glass fibers are subject to chemical attack by the alkalinity of the concrete, become brittle, and lose their effectiveness over a period of time. Nylon, polypropylene, and polyethylene fibers are not subject to chemical attack. Polypropylene fibers are available in several forms, such as smooth monofilaments, fibrillated monofilaments, fibrillated mesh, and collated fibrillated mesh. Properties of polypropylene FRC can vary somewhat depending upon the type of fiber used. Incorporation of polypropylene fibers into concrete can result in a small improvement in flexural and tensile strengths; however, these improvements are not always evident. Compressive strengths can be either increased or decreased. Fracture toughness can be increased, and shrinkage can be decreased.

k. Effects of polypropylene fibers on workability. Polypropylene fibers also affect the rheological properties of fresh concrete. Slump decreases as the volume concentration of fibers increases. The slump of a typical concrete can decrease by as much as 50 percent with the addition of 0.10 percent polypropylene fibers. Bleeding can be significantly reduced in polypropylene FRC.

l. Use of polypropylene fibers. Polypropylene FRC is typically used in nonload-bearing applications particularly where impact resistance is important. The use of polypropylene fibers for control of cracking in slabs is still being debated due to the amount of fibers required to positively affect the amount of cracking and the subsequent effect on workability.

10-8. Porous Concrete

a. General. Porous concrete is commonly used where either free drainage is required or where lower mass and lower thermal conductivity are required. The use of lightweight aggregates is not practicable or desired. It is normally produced by binding a gap-graded or a single-size aggregate with a cement paste. The structure of the material permits the passage of water but also provides moderate structural strength. Porous concrete has been used for drain tiles, drains beneath hydraulic structures to relieve uplift pressures, pavement edge drains, etc.

b. Types. At least three distinct types of porous concretes can be produced. These include cellular concretes made by introducing a preformed foam into the fresh mortar or causing the creation of gas bubbles in the mortar due to a chemical reaction; lightweight aggregate concrete made with natural or synthetic aggregates which are often extremely porous; or concrete which uses gap-graded or single-size aggregate and typically totally eliminates the fine aggregate fraction from the mixture (no-fines concrete). While each of these concretes are porous, they possess differing void structures. Cellular and lightweight aggregate concretes may contain large percentages of voids, but these voids are relatively noncommunicating. Porous concretes produced by intentional gap grading or without fine aggregate can result in concrete with high percentages of interconnected voids. The porous concretes with noncommunicating voids may absorb small amounts of moisture, but they do not allow rapid passage of water through the concrete. For this reason cellular and lightweight concretes should not normally be considered for the porous concrete applications previously noted and are not discussed in further detail.

c. Composition. Porous concrete is composed of coarse aggregate, cementitious material, and water. Occasionally, a small amount of fine aggregate can be used to increase the compressive strength and to reduce percolation. The coarse aggregate should comply with ASTM C 33 (CRD-C 133) size designations No. 8 (9.5-mm (3/8-in.) NMSA), No. 7 (12.5-mm (1/2-in.) NMSA), or No. 67 (19.0-mm (3/4-in.) NMSA). Both rounded and crushed aggregates have been used to produce porous concrete.

d. W/C considerations. The w/c of a porous concrete mixture is important to achieve the specified strength and to help create the proper void structure. A high w/c reduces the cohesion of the paste to the aggregate and causes the paste to flow downward and blind the void structure when the mixture is even lightly compacted. If the w/c is too low, balling will occur in the mixture, and the materials will not be evenly distributed throughout the batch. Experience indicates that the w/c should fall within a range of 0.35 to 0.45 for the paste to be stable and provide the best aggregate coating. The w/c - compressive strength relationship which is normally associated with conventional concrete does not apply to porous concrete.

e. Durability. The frost resistance of porous concrete is acceptable if the bonding paste is air entrained. However, because of the interconnected void system and high surface area of exposed paste in porous concrete, resistance to aggressive attack by sulfates and acids that may percolate through this concrete is questionable.

f. Percent voids. The percent voids, expressed as the air content, should be determined in accordance with ASTM C 138 (CRD-C 7). The air content should be 15 percent or greater, by volume, to ensure that water will percolate through porous concrete. The compressive strength of porous concrete will range from approximately 3,500 psi at 28-days age when the air content is 15 percent to approximately 1,500 psi when the air content is 25 percent. The percolation rate is proportional to the air content of porous concrete while the compressive strength is inversely proportional. The compressive strength also increases as the NMSA decreases.

g. Proportioning porous concrete mixtures. Although no ACI guidance for proportioning porous concrete currently is available, research conducted by the National Aggregates Association-National Ready Mixed Concrete Association (Meininger 1988) indicates that the dry-rodded unit weight of coarse aggregate as determined by ASTM C 29 (CRD-C 106) can be effectively used to proportion porous concrete. This approach to proportioning uses the b/b_o concept discussed in CRD-C 99 for proportioning normal weight concrete. The ratio b/b_o compares the amount of coarse aggregate in a unit volume of concrete with the amount of coarse aggregate in a like volume of dry-rodded coarse aggregate. This method automatically compensates for the effects of different coarse aggregate particle shape, grading, and density. Also, the b/b_o values for a range of NMSA normally used in porous concrete (9.5 to 19.0 mm (3/8 to 3/4 in.)) are very similar.

h. Placement. Proper construction methods are critical to the performance of porous concrete. Some compaction is needed during placement and the coarse aggregate on the top surface needs to be properly seated to reduce ravelling of the surface. Small steel wheel rollers have been used with some success for compaction. Curing is very important since porous concrete can dry very rapidly. Curing is vital to the continued hydration of the top surface. The level of compaction should be considered in the mixture proportioning study. If the porous concrete is compacted too much, the void content may be reduced below 15 percent, and flow channels will be plugged. Too little compaction will cause the concrete to have a very high void content and will result in low strength. Test specimens should be compacted to the same density as will be obtained in the field. This may require some experimentation in the laboratory to obtain comparable compaction in the field and the laboratory.

10-9. Flowing Concrete

a. General. Flowing concrete is defined by ASTM C 1017 (CRD-C 88) as "concrete that is characterized as having a slump greater than 7-1/2-in. while maintaining a cohesive nature." It can be placed to be self-leveling, yet remaining cohesive without segregation, excessive bleeding, or extended retardation. Flowing concrete can be used in congested areas where members are reinforced or unusually shaped or in areas of limited access. Flowing concrete pumps easily, and therefore, the concrete pumping distance and rate are increased. Proper consolidation around reinforcement is more easily achieved with flowing concrete than normal-slump concrete, and less vibration is required. Proper vibration is necessary for complete consolidation and bond to reinforcing steel.

b. HRWRA. Flowing concrete is produced by the addition of a normal (Type I) or a retarding (Type II) HRWRA, as described by ASTM C 1017 (CRD-C 88). These admixtures are generally identical to those described by ASTM C 494 (CRD-C 87) as HRWRA's, Types F and G, respectively. Flowing concrete cannot be produced by the addition of water since it will lose the cohesiveness necessary to minimize segregation. The amount of HRWRA required to produce flowing concrete varies depending upon the cement type, w/c, initial slump, temperature, time of addition, concrete mixture proportions, and the type of admixture. Concretes having lower initial slumps generally require larger amounts of HRWRA to produce flowing concrete than do concretes having higher initial slumps. HRWRA are also generally more effective in concrete having higher cementitious material contents.

c. Proportioning flowing concrete. Mixture proportions for flowing concrete usually contain more fine material than a conventional concrete mixture. This is necessary to achieve a flowable consistency without excessive bleeding or segregation. The fine aggregate content is usually increased by 3 to 5 percent, and in some cases, an increase in cement or pozzolan may be necessary. Since HRWRA's are usually added in large volumes, the water in the admixture must be accounted for in calculating w/c and yield. Higher dosages of air-entraining admixture are usually required to maintain proper air content in flowing concrete. The air content should be monitored regularly at the point of discharge into the forms so that the dosage of air-entraining admixture can be adjusted as necessary to maintain the air content within the specified range. The slump should be measured prior to addition of the HRWRA to assure that an excessive amount of water has not been added to the batch. After the HRWRA is added and thoroughly mixed into the concrete, the resulting slump should be within the specified range.

d. Flowing concrete fresh properties. Flowing concretes may exhibit a rapid slump loss depending on a variety of factors. Concrete temperature, cement composition, and cement content will influence the rate of slump loss. Also, flowing concrete made with plasticizing admixtures can lose much of its slump in as few as 30 minutes. Plasticizing admixtures must be measured accurately and discharged onto the concrete properly regardless of where their addition occurs. Additional dosages of HRWRA can be used when delays occur and slump is lost. Up to two additional dosages have been used successfully. In general, the compressive strength is unchanged, but the air content is decreased with additional dosages of HRWRA. The characteristics of flowing concrete at the time of finishing should be similar to that of conventional concrete with the same materials. Properly proportioned flowing concrete should not exhibit objectionable bleeding. As with the finishing of conventional concrete, proper timing of each finishing operation is imperative.

e. Flowing concrete hardened properties. The compressive strength, flexural strength, drying shrinkage, creep, and permeability of flowing concrete is not significantly different than that of lower slump concrete having the same w/c and air content. The air-void system may have larger bubble spacing factors and a decrease in the number of voids per inch compared to the initial concrete, yet satisfactory frost resistance is still achieved in most cases.

10-10. Silica-Fume Concrete

a. General. The use of silica fume as a pozzolan in concrete produced in the United States has increased in recent years. When properly used, it can enhance certain properties of both fresh and hardened concrete including cohesiveness, strength, and durability. Silica-fume concrete may be appropriate for concrete applications which require very high strength, high abrasion resistance, very low permeability, or where very cohesive mixtures are needed to avoid segregation.

b. Properties of silica fume. Silica fume is a by-product of fabrication of silicon or ferrosilicon alloys. It is a very fine powder having a medium to dark gray color. It is available as loose powder, densified powder, slurry, and in some areas as a blended portland-silica-fume cement. Silica-fume particles are spherical and are typically 100 times smaller than portland-cement grains. It typically has an SiO_2 content of 85 to 98 percent. It appears that concretes benefit from both the pozzolanic properties of silica fume as well as from the extremely small particle size. Silica fume is generally proportioned as an addition, by mass, to the cementitious materials and not as a substitution for any of those materials.

c. Effect on water demand and bleeding. Silica fume has a great affinity for water because of its high surface area, and this is reflected in the concrete which contains it. The increased water demand of concrete containing silica fume can be overcome with the use of a WRA or HRWRA and to a lesser extent by reducing the fine aggregate content of the mixture. Silica-fume concrete exhibits less bleeding than conventional concrete because the high affinity of silica fume for water results in very little water left in the mixture for bleeding. Silica-fume particles attach themselves to adjacent cement particles and reduce the available channels for bleeding.

d. Effect on cohesiveness. Concrete containing silica fume is more cohesive and less prone to segregation than a comparable mixture without fume; however, it also tends to lose slump more rapidly. Silica-fume additions greater than 10 percent should generally be avoided because the resulting concrete mixture will become "sticky" and require more vibration for proper consolidation. A slump increase of approximately 2 in. may be necessary to overcome this problem and to maintain the same consistency for some length of time. On the other hand, some increase in cohesiveness is an advantage in both flowing and pumped concretes.

e. Effect on air entrainment. The dosage of AEA required to produce a particular air content in concrete increases significantly with increasing amounts of silica fume. The amount of AEA needed in silica-fume concrete to entrain a specified amount of air may be as much as five times greater than that required for similar concrete without fume. It may also be difficult to entrain more than 5 percent air in concrete containing high silica-fume contents.

f. Effect on plastic shrinkage. When the curing conditions allow a faster rate of evaporation of water from the surface of fresh concrete than the water replaced by bleeding from the concrete underneath, plastic shrinkage cracking will occur. Therefore, all admixtures and pozzolans which reduce bleeding of fresh concrete make it more prone to plastic shrinkage cracking. This is particularly true for silica-fume concrete in which bleeding is significantly reduced. The problem can become very serious under curing conditions of high temperature and high wind velocity which favor faster evaporation of water from fresh concrete surfaces. A light fog spray of water can be used to keep surfaces from drying between finishing operations, or a sheet material can be used to cover the surface. Moist curing should begin immediately after finishing and should continue for a minimum of 14 days.

g. Effect on strength and modulus of elasticity. Strength development characteristics of silica-fume concrete are similar to those of fly ash except that the results of the pozzolanic reactions of silica fume are evident at early ages. This is because silica fume is a very fine material with a very high glass and silica content. However, since silica fume increases the water demand of a mixture, use of a WRA or HRWRA to offset water demand is necessary to take full advantage of silica fume’s full potential for increasing strength. The ratio of flexural to compressive strength of silica-fume concrete follows the same pattern as conventional concrete. There are no significant differences between the Young’s modulus of elasticity of concrete with and without silica fume. However, very high-strength concretes tend to be more brittle, and this is also true of high-strength silica-fume concrete.

h. Effect on permeability and durability. Pozzolans and GGBF slag often significantly reduce the permeability of concrete due to their influence on the fine pore structure and interfacial effects. Silica fume is a much more efficient pozzolanic material than natural pozzolans or fly ash, and therefore, it decreases concrete permeability dramatically. However, silica-fume concrete must still be properly air-entrained if it is subject to critical saturation and repeated cycles of freezing and thawing. Silica-fume concretes have exhibited reduced chloride-ion permeability, enhanced resistance to attack from sulfates and other aggressive chemicals, and enhanced abrasion resistance. While abrasion resistance is more dependent upon the hardness of the aggregate than upon that of the paste, the addition of silica fume can increase the abrasion resistance of concrete when hard aggregates are unavailable or cannot be economically justified, and inferior aggregates must be used.